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MODELLING OF HYDRODYNAMIC PHENOMENA OCCURRING IN REFINING LADLES FOR HIGH-CARBON Fe-Si ALLOYS

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This paper presents the results of research conducted with the use of water physical model of refining ladle for production of high-carbon FeSi alloys. The purpose of the research was to determine the possibilities to enhance the efficiency of the production process by using combined gas injection into the bath. The research involved analysis of four variants of the experiment. Those variants varied in terms of the location of a purging plug fitted in the model bottom and the application of immersion lance to support the process. The research involved the analysis of changes in the hydrodynamic effects in the ladle model occurring as a result of the gas injection. The tests consisted in a qualitative analysis (process visualisation) in order to identify the movement of the modelling liquid and the mechanism of gas bubbles behaviour in the liquid.

Key words: Fe-Si alloys, refining ladle, combined gas injection, lance, physical modelling

INTRODUCTION

With the increasing quality requirements placed on producers of special-purpose steels, the demand for particularly low-emission ferroalloys is growing. Therefore, Re Alloys sp. z o. o. undertakes research initiatives aimed at developing an energy-saving, low-loss ferrosilicon production technology that would meet these requirements.

The offered technology enables the production of low-carbon ferrosilicon, which will be used both in the refining of high-quality special-purpose steels and in the processes of obtaining complex modifiers based on ferrosilicon [1].

The decarburization products in the developed low-carbon ferrosilicon smelting technology are CO, which is removed from the bath in the form of bubbles, and SiC, which due to its density is comparable to FeSi75% (SiC: 3 130 kg/m^3, FeSi75: 3 185 kg/m^3 at a temperature of 1 450 °C), remains in the metal bath as an impurity [1,2].

The required efficiency of removing impurities from the metal bath can be achieved in secondary metallurgy processes by injecting an appropriate gas mixture ($Ar+O_2$) through special purging plugs placed at the bottom of the refining ladle. According to the principles of hydrodynamics, this causes the SiC particles to float up and lock them in the slag. Supporting the process with additional gas injection through the top lance can enhance the effect. Intensive stirring of the melt promotes the coagulation process of SiC particles due to the increased possibility of their collision. It creates favourable conditions for larger inclusions and, as a result, has a positive effect on the possibility of their emergence at the border of the metal-slag division [1-3].

Physical modelling is an effective method for solving the problems of refining liquid metals by injecting gas into their volume. It enables to determine, from the point of view of the hydrodynamics of the process, parameters affecting its efficiency, such as: the impact of the design of the purging plug and its location at the bottom of the ladle; mechanism of creating a column of gas bubbles, type of gas dispersion in the bath volume, minimum bath homogenization time [4-6].

OBJECT OF THE RESEARCH STUDY

The research was conducted with the use of a ladle model representing a refining ladle of the volume of approx. 8 Mg of liquid FeSi75 metal, used in the ferroalloys smelter - Re Alloys sp. z o.o.

The ladle model was made on a linear reduction scale, at a scale of 1:3, in accordance with the requirements of probability theory [7,8]. To facilitate the process of building the model, a slight simplification of its geometry was introduced, but this did not significantly affect the results of the established research program. The simplification consisted in taking into account the convergence of the ladle model. Although convergence affects some thermal effects in the ladle, its effect on hydrodynamic phenomena is negligible.

The designed ladle model assumes the possibility of simultaneous injection through one or two purging

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Table 1 **Design parameters of the ladle model (scale 1:3)**

Parameter	Unit	Value
Volume (up to the liquid level)	m^3	0,072
Height (liquid level)	m	0,40
Total height	m	0,54
Diameter	m	0,48

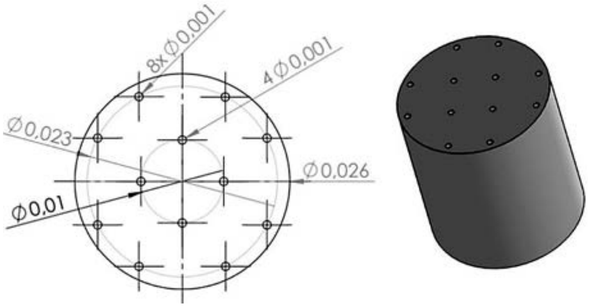

Figure 1 Design of the purging plug model - dimensions / m

plugs located at the bottom, additionally supported by the top lance. The basic dimensions of the model are presented in Table 1.

Figure 1 shows a purging plus model applied in the model testing. The model was printed with 3D printer in the Fused Deposition Modelling (FDM) technology.

In accordance with the assumptions, the industrial gas flow conditions were appropriately transformed (gas flow in the industrial installation is 750 l/min) into the model one. In accordance with the guidelines, the calculation of dynamic similarity condition of gas flow in the model to the real condition was performed based on the modified Froude`s criterion [9,10]. Table 2 shows the test program with the gas flow values calculated in the model.

Table 2 **Programme of tests performed on a water model**

Exp. variant	Method for gas introducing			Intensity of gas / dm^3/min	
	P1	P2	L	purging plug	lance
A1	X	–	X	13,4	13,4
A2	–	X	X	13,4	13,4
A3	X	–	–	26,8	–
A4	–	X	–	26,8	–

Figure 2 shows the marking and location of the purging plugs fitted in the bottom of the model and the location of the lance for the analysed experimental variants.

The course of the experiments was recorded with a camera. The video material provided results that allowed for full identification of the movement of the model liquid in the ladle volume and the mechanism of behaviour of gas bubbles in the liquid. An aqueous solution of $KMnO_4$ was used as a tracer. A series of tests were carried out for each variant of the experiment.

The analysis of the experimental results consisted in determining the optimal conditions for refining FeSi alloys, taking into account the hydrodynamics of the process.

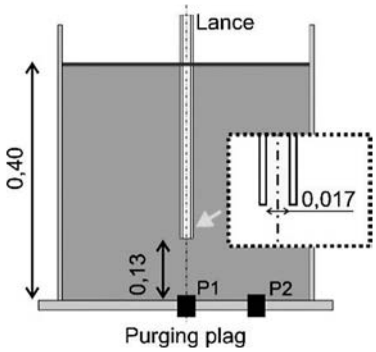

Figure 2 Parameters adopted for model tests - dimensions / m

RESULTS AND DISCUSSION

Figures 3-6 show exemplary results of tests, illustrating the movement of the model liquid and the mechanism of gas bubbles behaviour in it, for all the variants.

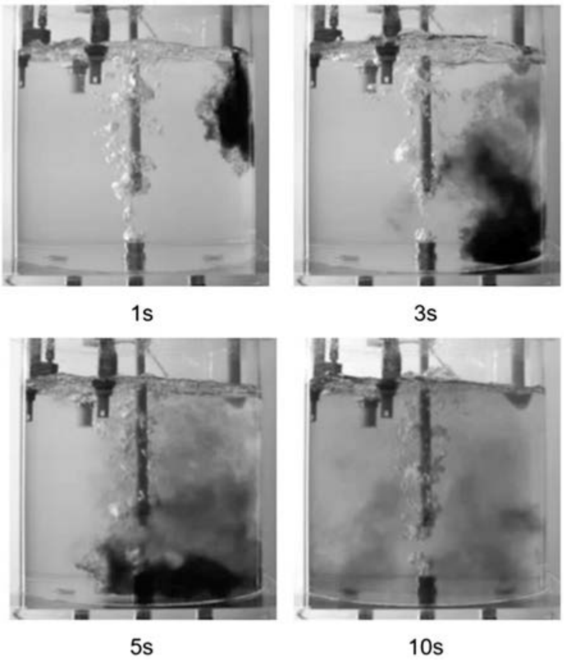

Figure 3 Results of model tests - variant A1

In variant A1 (see Figure 3), where the purging plug was located on a common axis with the gas lance, an interaction between gas bubbles coming from two sources was observed. This involved violent collisions of bubbles moving in opposite directions, which resulted in their fragmentation. Fragmentation had a beneficial effect on the formation of the gas column and the level of gas dispersion in the volume of the model liquid. The effect of this interaction was also a reduction in the energy of gas bubbles as a result of energy consumption for interaction in the zone between both streams. The basis for this conclusion was the observed slight decrease in mixing intensity.

In the experimental variants A2 in which the purging plug was away from the axis of the gas lance (see Figure 4), no interaction between the streams of both sources was observed. Due to the high flow rate of the gas source, the bubbles emerging from the lance formed large clusters and, flushing the sides of the lance, rose towards the surface of the modelling liquid. However, the behaviour of gas bubbles flowing from the purging plug was characterized by the formation of large gas bubbles already in the outflow zone and the formation of a classic gas column expanding towards the surface of the modelling liquid. This phenomenon was caused by the proliferation of gas bubbles with a decrease in the pressure of the modelling liquid column.

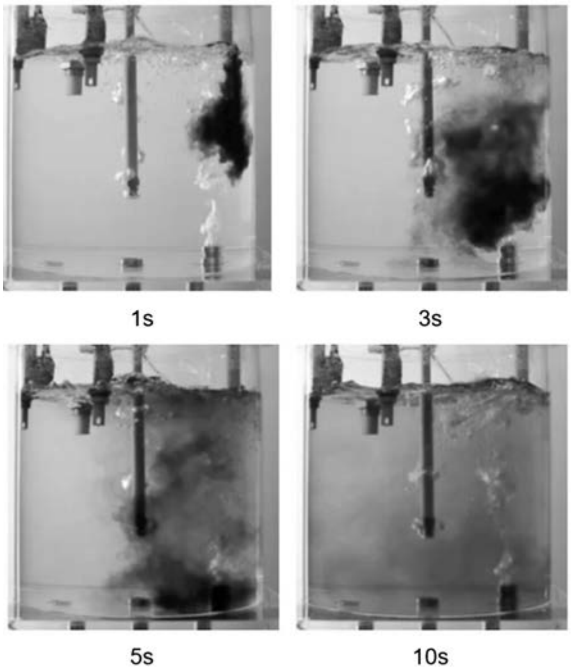

Figure 4 Results of model tests - variant A2

In the case of the remaining variants of the experiment A3 and A4 (see Figures 5 and 6), a typical way of creating gas columns was observed. As in the case of the two previous variants (with a lance), a tendency was noticed to create a spiral path of gas bubbles rising to the surface. Due to the high flow of the gas source, the bubbles merged into large conglomerates and rose towards the surface of the modelling liquid.

To sum up, such a high flow rate of the gas source promoted the extension of the turbulent flow of the modelling liquid in the ladle volume due to its high energy, and consequently also promoted the homogenization of the process. On the other hand, the expansion of the turbulent flow areas significantly limited the refining capabilities of the process and could even cause secondary contamination of the bath.

In the next stage, the results of the tests were analysed in terms of the behaviour of the modelling liquid in the volume of the modelling ladle under the influence of gas stream injection.

In the A1 variant (see Figure 3), where gas injection took place in a combined manner through a purging plug placed in the axis of the ladle and gas lance, a circular motion of the modelling liquid was observed. The movement occurs in the zone of the ladle axis, where, as a result of the action of gas bubbles, the liquid phase escaped to the surface and then fell in the wall zone. This resulted in the creation of a mixing zone in the lower part of the ladle model, which had a positive impact on the homogenization capabilities of such a system.

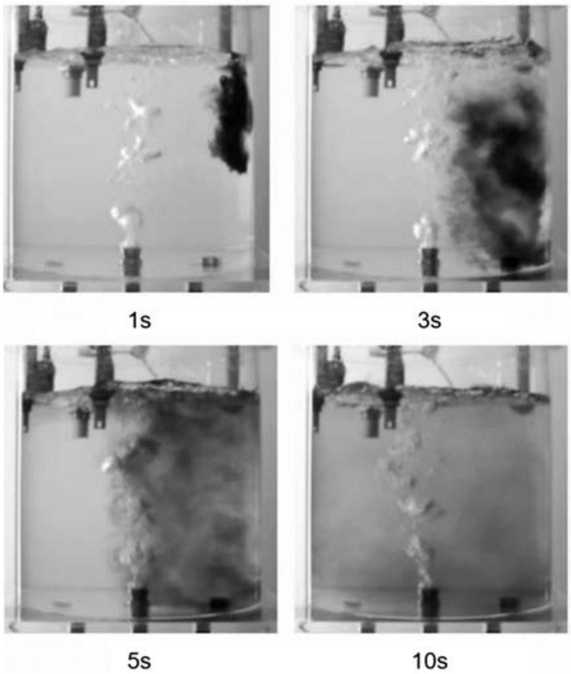

Figure 5 Results of model tests - variant A3

A different nature of the flow occurred in the A2 variant (see Figure 4), in which the purging plug was located outside the axis of the lance and gas lance. In such a case, there was a significant interruption in shaping the movement modelling the liquid circulation from the axis towards the ladle walls. Under the influence of gas bubbles injected by the purging plug, the modelling

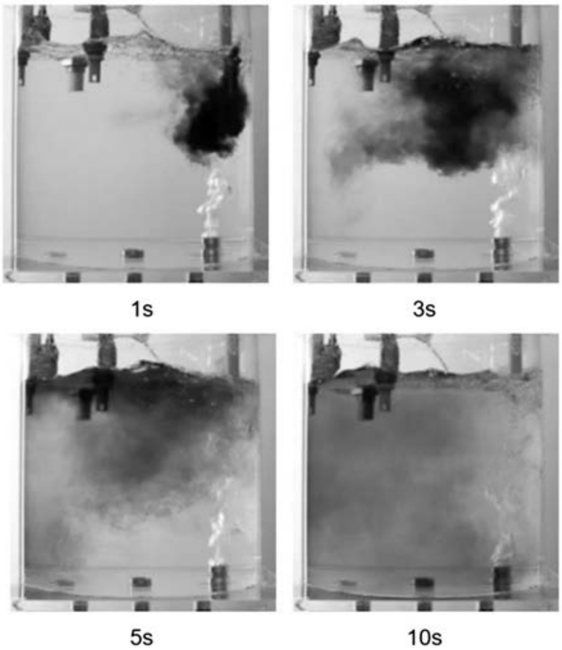

Figure 6 Results of model tests - variant A4

liquid tended to circulate throughout the volume, but gas bubbles injected by the lance effectively interrupted this process. The disturbance had a beneficial effect on the homogenizing ability of the modelling liquid, as it caused an extension of the turbulent flow area in the refining ladle. An unfavourable phenomenon, as in the remaining variants of the experiment, was excessive waving of the surface of the modelling liquid caused by strong streams of injected gas.

For variant A3 (see Figure 5), the nature of the modelling liquid flow was observed similar to that in variant A1. As a result of the outflow of gas bubbles from the purging plug located in the axis of the bottom of the model ladle, the liquid stream in this zone was raised to the surface. When it reached the surface, it bounced and fell in the walls zone, creating a circulation movement. However, this movement occurred over the entire height of the modelling liquid column, unlike variant A1, where this movement was blocked in the zone of action of the gas bubbles, between the lance and the purging plug.

In the case of the A4 variant, in which the purging plug is located outside the axis of the ladle (see Figure 6), the hydrodynamic conditions were different than in the other variants. However, they met the expectations, which means that in this case the formation of circular flow was also observed, but in the entire volume of the ladle. The tracer was lifted together with the modelling liquid towards the surface along the gas column and fell in the area of the opposite wall of the ladle. In this variant of the experiment, a tendency was observed to create zones with less turbulence in the zone of the ladle axis.

To sum up, it was found that in all experimental variants, a strong gas stream injected into the model volume had no major impact on its homogenization, however, the hydrodynamic conditions created prevented effective refining of the bath.

CONCLUSIONS

The research conducted was qualitative in nature. The mechanism of formation of gas bubbles injected into the modelling liquid, the mechanism of gas column formation, gas dispersion in the modelling liquid and the mechanism of movement of the modelling liquid in the volume of the refining ladle were carried out. The obtained results justify the conclusion that due to the high flow rate of the injected gas, the mechanism of gas bubble formation in the volume of the refining ladle is unfavourable. This favours the homogenization of the bath, but its structure is unfavourable in terms of refining properties. Due to the strong interaction of gas bubbles and the surface of the modelling liquid, a risk of secondary metal contamination at the metal-slag interface can be predicted.

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Note: English translation by Maria Obłój.